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Abstract - **The release of object during robotic micromanipulation operations stays a challenge. The adhesion forces have to be known to improve micromanipulation tasks. Adhesion models build from macrophysics (continuum mechanics) or from nanophysics (atomic scale interactions) do not fit well experiments on the microscale. This is due to some phenomenon which are specific to the microphysics. Some of them are developed in this article. First, it is shown that the charges distributions observed on the microscale would have negligible effects on the nanoscale but disturbs significantly micromanipulation. Secondly, the impact of both chemical functionalisation and physical structuration of the surfaces on microscale are presented. Third, during the contact between two objects, the van der Waals forces induces significant local deformations on the microscale contrary to nanosclae where the deformation is negligible. This article shows some typical differences between microscale and nanoscale.**

Keywords - **Microhandling, modeling, interaction forces**

I. Introduction

Nowadays, micro-grippers are mostly not force-controlled so forces around one thousand times greater than the adhesion force are commonly applied to guarantee the detachment of the two micro-objects. A better prediction of these forces could improve tele-operating manipulation thanks to haptic feedback [1]. Moreover, modeling these forces on the microscale is necessary for automatic tasks and for creating simulators for testing new manipulation strategies. A better knowledge of physical phenomenon enables to exploit their effects rather than undergo them. For example, (i) coating or functionalizing the handling area could prevent from adhesion forces or increase it [2]; (ii) optimization of roughness can be achieved to minimize adhesion [3], [4] ...

Micromanipulation is mostly based on top-down strategies so microgrippers are still catching micro-objects in the same way that macrorobots e.g. by pressing objects between two compliant fingers. However their design has to be adapted to the differences between macro- and microphysics. Moreover adhesion forces on the microscale are due to phenomena which have nanoscale origins. So micromanipulations use top-down tools but are modeled with bottom-up methods. Knowledge of the two scales can be used on the microscale but requires special attention on validity domains.

Phenomena that influence interactions between micro-objects have to be studied in order to highlight their relative influence according to the scale. Models from nanophysics presented in section II will be used to bring out each phenomenon influence on the microscale. Four specific phenomena influenced by scale effects between micro- and nanoscales are presented in this paper. It is shown in the section III that electrostatic forces prevail on van der Waals forces on the microscale. Section IV deals with the impact of chemical functionalisation on interaction force. Roughness and surface structuration are studied in section V. The section VI focuses on the coupling between the deformation and the van der Waals forces.

II. Modeling the microworld

Differences between macro- and microphysics is now well established but what about the micro- and nanophysics ? As for macro- and micromanipulation, miniaturization of micromanipulation processes is not the right way to do nanomanipulation. Miniaturization is not just a technical issue; it also must take into account differences in physics.

A. From nano phenomena ...

The main issue of the micromanipulation is to release micro-objects properly. The corresponding force is the pull-off force which is the force to apply to break contact surface between two objects. This force is usually considered as normal to the contact. In dry environment they are induced by several phenomena as van der Waals, electrostatic and capillary forces [5].

Each of them depend on several parameters (materials, roughness, humidity, temperature) and are due to nanomechanisms.

At the atomic level, van der Waals force is the attraction force between two single atoms. It is commonly assumed to be an additive force so for two objects S_1 and S_2 distant from r, the total van der Waals force is the double sum of forces applied on atom of S_2 by atoms of S_1 [6], [7], [8]. Adhesion is currently modeled by considering a minimal distance $z = z_0$ between both objects. z_0 is usually set to $0.3\,\mathrm{nm}$ which is the equilibrium distance between two atoms in vacuum. All along this paper, we choose to illustrate phenomena with adhesion between a glass sphere of radius r_2 and a plane. The van der Waals force induced by this geometry is:

$$F_{vdw} = -\frac{Ar_2}{6z^2}, \tag{1}$$

where $z = z_0$ for contacting objects and A is the Hamaker coefficient ($A = 6.5\ 10^{-20}$ J for glass).

Electrostatic forces are due to surface charges added by friction or chemical treatment (cleaning, oxidization ...). They are modeled in the same way as the van der Waals forces replacing volume atoms distribution by a surface charge distribution. The electrostatic force applied by the plane (surface charges σ_1) on the sphere (surface charges σ_2) is:

$$\overrightarrow{F}_{pull-in} = q_2.\overrightarrow{E}_1 = 2\pi r_2^2 \frac{\sigma_1\sigma_2}{\epsilon_3\epsilon_0}\overrightarrow{n_1} \tag{2}$$

where ϵ_0 is the vacuum permittivity.

Capillary forces F_{capil} are due to water meniscus created thanks to ambient humidity or adsorbed layers. This paper does not deal with capillary effects.

B. ... to the microscale modeling

The models presented above can be used to model pull-off forces on the microscale. So the most natural way to model pull-off force is to sum them:

$$F_{po} = F_{vdw} + F_{es} + F_{capil}. \tag{3}$$

This bottom-up model of pull-off forces let us understand origins of the adhesion.

Top-down models are also currently used to model adhesion. Energetic modeling derived from continuum mechanics can be used for estimating pull-off forces between objects with simple geometries. The most famous models are the JKR [9] and the DMT [10] models. They are wildly used but they do not consider the influence of electrostatic and capillary forces. This kind of model is not flexible: adding a complementary force or changing geometry is complex because of the model computation method.

C. Force measurements

Pull-off forces are measured thanks to an atomic force microscope (AFM). In the present case, beads are fixed on an AFM cantilever (Fig. 1) whose relative position to the studied plane is controlled by a micropositioning device. The cantilever has a low stiffness (between $0.2\,\mathrm{N/m}$ and $0.3\,\mathrm{N/m}$ in our case) in order to measure weak non-contact forces.

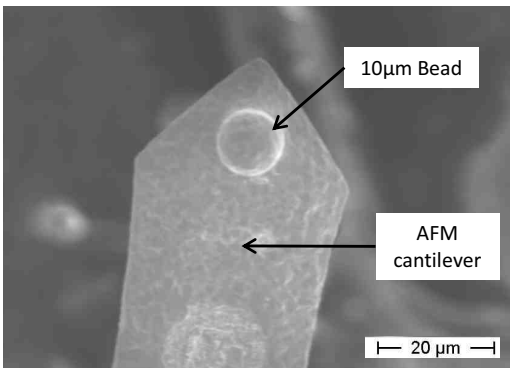


Fig. 1. A microbead is fixed on an AFM cantilever in order to measure pull-off forces. Force measurements have been performed on gold coated beads (see photo) and silica beads.

In this article, we chose to take advantage of both the bottom-up and the top-down approaches to model pull-off forces on the microscale. The flexibility of eq. (3) will let us studying the effect of each part of the pull-off force according to the nanoscale point of view. Moreover, the deformations will be taken into account too in order to stay close to macroscopic theories.

III. Scale effect on electrostatic forces

There are usually fluctuations in charges distributions on micro-nano objects so associated forces are not repeatable and then are currently considered as a perturbation. As an example, the maximum amplitude of electrostatic force for silica beads is first estimated in this section. The resulting distribution of charges is then used to illustrate the scale effect on electrostatic forces.

Two kinds of attractive non-contact forces can be observed between micro-objects: the van der Waals forces and the electrostatic forces. They can be measured when pull-in occurs. Pull-in is a jump to the contact that occurs when the bead is approached to the plane. The corresponding force is defined as the strongest attractive force observed just before the contact. One way to determine the predominant force consists in looking at the interaction range. Indeed electrostatic forces have a longer interaction range than van der Waals forces (typically several micrometers to tens of nanometers for van der Waals forces). In case of an interaction between a silicon plane and a borosilicate sphere, typical surface charges about $\sigma = 0.15\,mCm^{-2}$

have been observed experimentally [12]. This level of charge induced by tribolectrification is typically lower than those obtained by chemical functionalisation in liquid (see section IV).

A. Scale effect consequences on pull-off measurements

In order to evaluate the effect of electrostatic forces on adhesion phenomena, we chose to compare them to the other cause of adhesion: the van der Waals forces. In order to study the influence of scale effect on forces, it can be noticed that the van der Waals forces are proportional to the radius of the bead (1) whereas, according to (2), electrostatic forces are proportional to its square. This difference induces different scale effects on both phenomena. In the case of borosilicate glass, it can be seen on Fig. 2 that the influence of the electrostatic forces have to be considered for objects whose size is greater than $1\ \mu\mathrm{m}$. On nanoscale, the proportion of the pull-off force due to the electrostatic forces becomes negligible compared to these due to van der Waals forces.

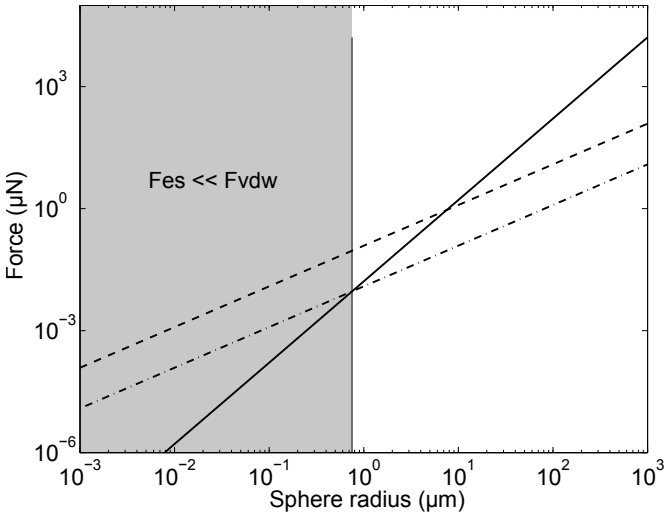


Fig. 2. Electrostatic (solid line) and van der Waals (dashed line) forces between a sphere and a plane according to the sphere radius. The electrostatic force is considered as negligible as it is lower than the tenth of the van der Waals forces (dash-dot line). Considered materials are borosilicate glass, with $A = 6.5\ 10^{-20}$ J, $r_0 = 0.3$ nm and $\sigma = 0.15\ 10^{-3}\mathrm{C/m^2}$.

It is possible to control the charge density on the surface by chemical treatments [3] (see section IV below) or using conductive materials. However, in the case of non-conductive and non-treated materials, the charge density could not be controlled and fluctuate. On microscale, the adhesion is linked to the charge density and its variations; it is therefore very difficult to make repeatable pull-off measurements with non-conductive micro-objects.

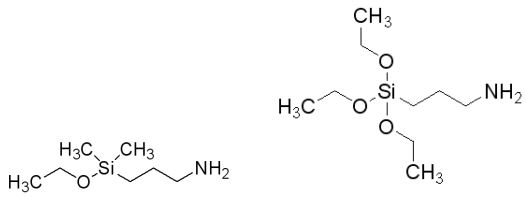
At the nanoscale, it is possible to measure the van der Waals forces between non-conductive materials without variations observed on the microscale because the electrostatic forces can be considered as negligible compared to the van der Waals forces. This explains why the van der Waals theory has been validated experimentally on the nanoscale for all types of materials, even non-conductive.

IV. Chemical functionalisation and electrostatic forces

Based on the fact that electrostatic forces can be a predominant effect on microscale. Electrochemical effects can be exploited in order to control electrostatic surface density via chemical equilibrium between the surface and the liquid medium. Surface functionalisation of both object and gripper can be obtained by different methods (physisorption, grafting...). Two chemical functionalisations have been tested (see in figure 3):

- the silane, 3 (ethoxydimethylsilyl) propyl amine (APTES);
- the silane, (3 aminopropyl) triethoxysilane (APDMES).

Both chemical compounds (APTES, APDMES) used to surface functionalisation are amine functions NH_2 which can protonated or ionised to NH_3^+ according to pH. In acidic pH, the anime is totally ionised, then the ionisation decreases and is null in basic pH (between pH 9 and 12). Our principle is also based on the protonation of silica, which enables to switch from SiO_2 to SiO^- according to the pH. The combination of both effect enables to obtain a surface whose electrostatic charges switch from a positive value for low pH to a negative value for high pH.

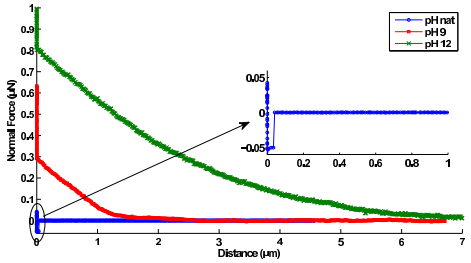


(a) APDMES (b) APTES

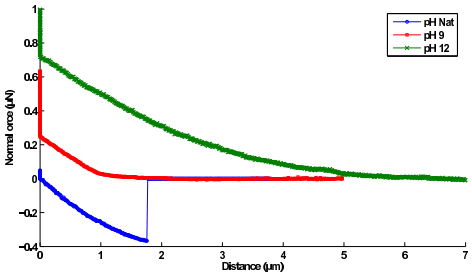
Fig. 3. Molecules used for the silica functionalisation.

Pull-off force measurements were done on a functionalized plane using a cantilever with a non-funtionalised sphere. The results of the pull-in and pull-off forces is presented in figure 4.

In this figure, we noted that the pH influences significantly the forces between the cantilever and the surface. At natural pH, a attractive pull-in is measured (near -60 nN, Figure 4(a)) with an important pull-off (- 350 nN, Figure 4(b)). When the pH increases the pull-in force is inverted and becomes repulsive respectively 280 nN and 770 nN at pH 9 and 12. Moreover, the adhesion forces disappear. In order to be able to extrapolate this result to other geometries, the electrical



(a) Approach measurement



(b) Retract measurement

Fig. 4. Force-distance curve for the APTES functionalised substrate in wet medium at different pH obtained with a tip whose spring constant is 0.3 N/m.

surface density induced by the functionalisation have been studied. The repulsive electrostatic force applied by the plane (surface charges σ_1) on the object (surface charges σ_2) is defined in (2), where surface charges have been established in [3], [4] (see in table I).

TABLE I
ELECTRICAL SURFACE DENSITY OF THE FUNCTIONALISED SURFACE IN FUNCTION OF THE PH

	APTES	APDMES
pH	σ_1 (mC/m^2)	σ_2 (mC/m^2)
pH 2	+3.8	+3.6
pH nat	+1.7	+1.9
pH 9	-0.8	-0.6
pH 12	-2.1	-2.1

V. IMPACT OF ROUGHNESS ON VAN DER WAALS FORCES

An other important parameter which modifies significantly the adhesion is the roughness. Using nanostructuration of surfaces, the roughness of the surface can be controlled. It enables to study properly the impact of roughness on interaction forces and also to control the roughness in an application case.

Let us consider the nanostructure described in figure 5 which represents the position of nanoscaled *PS* spheres on a surface. These nanostructurations have been built by the EMPA institute, Thunn, Switzerland[2] using self-assembly methods. In an application case and also during force measurements the location of the sphere on the probe up the structured surface cannot be controlled precisely. When the probe r_1 is approaching, it touches the nanospheres r_1 on a non-controlled position. We have shown that the force is included between a minimum and a maximum which verifies [2]:

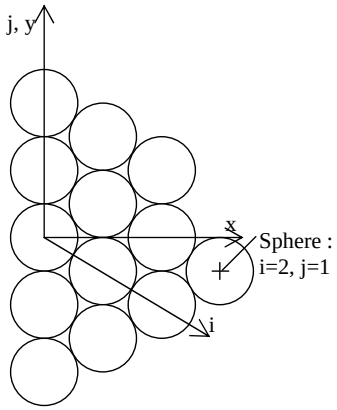


Fig. 5. Arrangement of the *PS* spheres on the substrate.

$$F_{Tvdw_{min}} = \sum_{i,j}^{\mathbb{Z}^2} \frac{A_{12} r_{12}}{6 z_{ij_{min}}^2} . \frac{r_2 + z_0 + r_1}{r_2 + z_{ij_{min}} + r_1} \tag{4}$$

$$F_{Tvdw_{max}} = \sum_{i,j}^{\mathbb{Z}^2} \frac{A_{12} r_{12}}{6 z_{ij_{max}}^2} . \frac{\sqrt{(r_2 + z_0 + r_1)^2 - (4/3.r^2)}}{r_2 + z_{ij_{max}} + r_1} \tag{5}$$

where:

$$z_{ij_{min}} = ((r_2 + z_0 + r_1)^2 + 4 r_2^2 (j^2 - ij + i^2))^{\frac{1}{2}} - r_1 - r_2 \tag{6}$$

$$z_{ij_{max}} = ((r_2 + z_0 + r_1)^2 + 4 r_2^2 (j^2 - ij - i - j + i^2))^{\frac{1}{2}} - r_1 - r_2 \tag{7}$$

$$r_{12} = r_1 . r_2 / (r_1 + r_2) \tag{8}$$

The comparison between value predicted by the model and the measurement, plotted in 6, shows a good concordance. So 90 % of the experimental points validate the model. The other 10% of the experimental points are very near to the predicted value, just few *nN* below the model.

The second results deals with the determination of a minimum of the interaction force which represents an optimum of adhesion reduction in the applicative field of micromanipulation. In our experimental case, the optimum *radius* r_2 in order to minimize the adhesion is between 45 and 100 *nm*. If the *radius* r_2 is lower than this optimum, more and more spheres should be considered in the sum thus increasing the force. This value depends of the diameter of borosilicate sphere

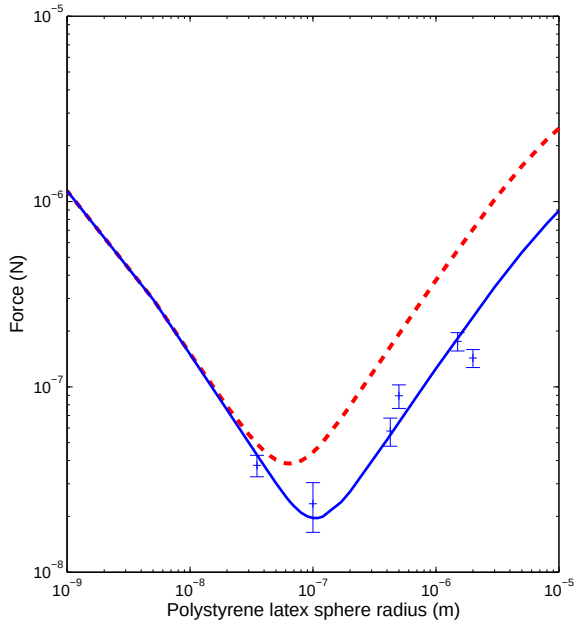


Fig. 6. Comparison between the model (minimal force, blue solid line, and maximal force, red dash line) and experimental measurements (error bar) on the structuring surface for borosilicate 20 μm in function of the nanostructuration r_1.

glue to the cantilever. The model can be extended to different diameter of sphere r_1 using (4) and (5).
The proposed model can be used to determine the diameter of the optimal *PS* particles spheres to be placed on a gripper to minimize adhesion force with a grasped sphere S_b. Experimentally, some *PS* spheres has been deposed on silicon grippers [13] (see in figure 7).

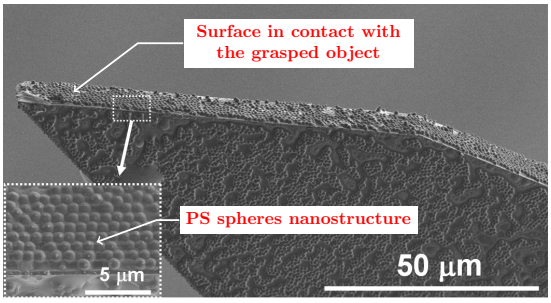


Fig. 7. Structuring gripper by *PS* particles of 1 μm : Joint work between EMPA institute, Thunn, Switzerland, and FEMTO-ST institute, Besançon, France [2]

VI. Influence of deformation on van der Waals forces

Van der Waals forces (1) are usually computed on non deformed objects but local deformations are able to significantly increase their value on microscale. Moreover, the greater part of van der Waals forces is due to the contact area, where both objects are the closest. Deformations should therefore be taken into account for the force calculation. This section shows that the coupling between van der Waals forces and deformations is also a characteristic of the microscale.

A. Coupling principle

Because of its short interaction range, the van der Waals forces are close to be a surface force. In this model, we chose to replace this local force by an equivalent external load which induces a deformation. This deformation increases the contact surface and then the global van der Waals forces too. This coupled problem can be seen as an algorithm that uses sequentially two models (Fig. 8). The first one computes van der Waals forces according to the object shape. The other one computes deformation shape according to an external load. An iterative calculation is able to converge to the physical equilibrium.

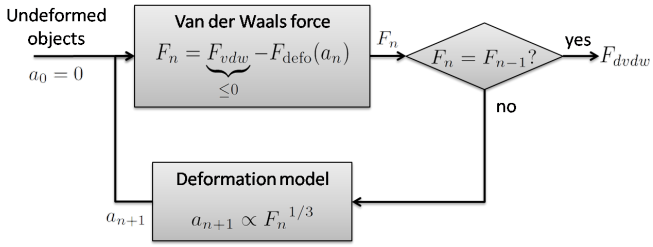


Fig. 8. Algorithm proposed for calculating the adhesion force F_{dvdw} between two objects using the coupling between deformation and van der Waals forces. The algorithm starts with non-deformed objects so the initial contact radius a_0 is set to zero. The van der Waals force F_n can be computed as the sum of a deformable dependent part F_{defo} and a non deformable one F_{vdw} [11]. The deformation model used comes from the Hertz theory.

This section deals with the contact between a sphere and a plane as an example. In order to highlight the influence of the scale effects on deformations, the contact geometry will be simplified. We chose to replace the deformed sphere by a truncated sphere. The high δ of the removed spherical hat is calculated thanks to the Hertz deformation model. It is then possible to calculate the van der Waals force between the truncated sphere and the plane according to δ (details of the calculation can be found in [11]) and then close the model (Fig. 8).

B. Model of the coupling

The adhesion force F_{dvdw} calculated using this modeling principle is presented on Fig. 9 in the case of silicon objects. A critical radius can be extract from the model equations [11]:

$$R_c = \frac{2E^2 z_0^7}{(1-\nu^2)^2 A^2}, \tag{9}$$

where E and ν are the mechanical characteristics of the objects. In the case of glass objects, $R_c = 0.5$ µm. If the

sphere radius is smaller than this critical radius R_c, the computed pull-off force tends to be the classical van der Waals force presented in eq. (1). So, on the nanoscale, the influence of deformation on van der Waals forces becomes negligible.

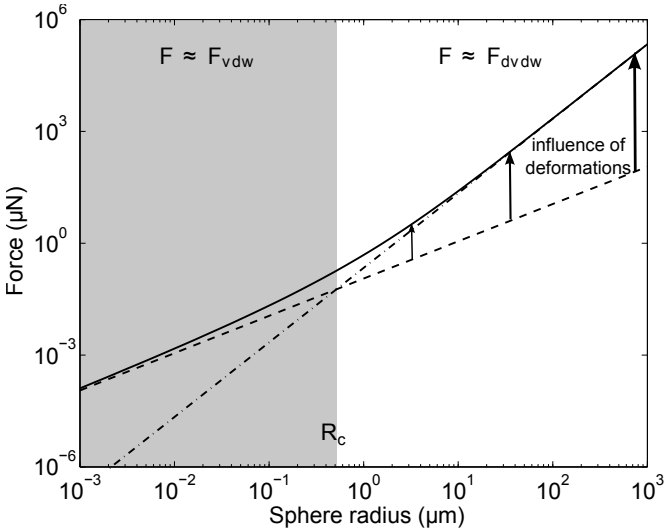


Fig. 9. Comparison of forces computed with classical and deformable van der Waals theories on nano and microscales. The numerical solution of the deformable van der Waals (dvdw) model (solid line) matches classical van der Waals (eq. (1), dashed line) on nanoscale and analytical formula (eq. (10), dash-dotted line) on microscale.

The influence of deformations on the pull-off force has to be only considered on the microscale. We have shown in [11] that on the microscale, for $r_2 \gg R_c$ the adhesion force tends to be:

$$F_{dvdw} = -\frac{A^3 r_2^2}{48 z_0^9 E^{*2}}. \quad (10)$$

The difference between both force models is increasing with the radius of the sphere. This asymptotic model is based on analytic formulation. A full numerical model that considers exact shapes thanks to finite element models should rather have a $R^k (k > 0)$ scale dependence.

This second scale effect highlights another characteristic of the microscale physics where deformations significantly increase van der Waals force.

VII. Conclusion

The micrometer seems to be a critical size where physics is changing and where couplings are appearing between several physical effects. Four features of physics on the microscale were highlighted in this paper: (i) electrostatic forces disturb micromanipulation whereas it seems to be negligible on the nanoscale, (ii) surface functionalisation enables to modify significantly interaction forces, (iii) roughness is a critical parameter of the pull-off force and (iv) the material deformations strongly increase the pull-off forces only on the microscale. Because of those scale effects, pull-off force measurements on the microscale present large variations whereas forces could be predicted easier on the nanoscale. It is well established that a top-down strategy is not well adapted to micromanipulation. We have shown that a pure bottom-up strategy based on the extrapolation of nanosciences is not a better way. Both macroscale and nanoscale effects have to be considered for microphysics modeling.

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